

# New Measurement of the $B^0_s$ Mixing Phase at CDF

Elisa Pueschel  
University of Massachusetts, Amherst  
on behalf of the CDF Collaboration

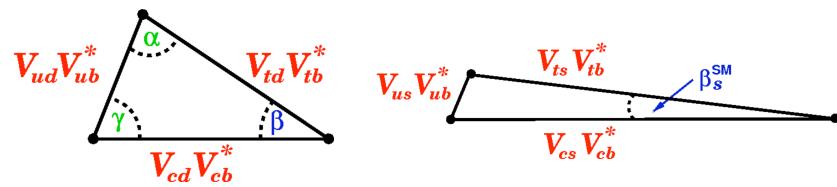
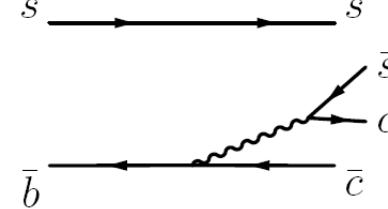
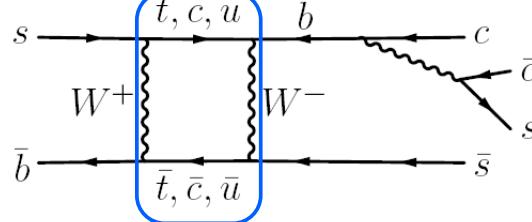
Heavy Quarks and Leptons, INFN  
October 13, 2010

# CP Violation in $B^0_s \rightarrow J/\psi \varphi$

- Analogous to measurement of  $\sin 2\beta$
- CPV in the interference between direct decays and decays via mixing



Could have new physics participation in loop process



- Use unitary property of CKM matrix to derive unitary triangles

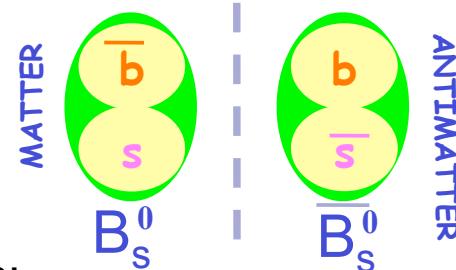
Large measured  $\beta_s$  must be due to new physics participation!

$$\beta_s = \arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) \approx 0.02$$

# CP Violation in $B_s^0$ Mixing

Time evolution of states is given by:

$$i \frac{d}{dt} \begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} = \left( \mathbf{M} - \frac{i}{2} \boldsymbol{\Gamma} \right) \begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix}$$



Flavor eigenstates → heavy and light mass eigenstates:

$$|B_s^H\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle \quad |B_s^L\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle$$

Observables:

$$\boxed{\Delta m_s} = m_H - m_L \approx 2 |M_{12}| \quad \text{Mass difference/oscillation frequency}$$

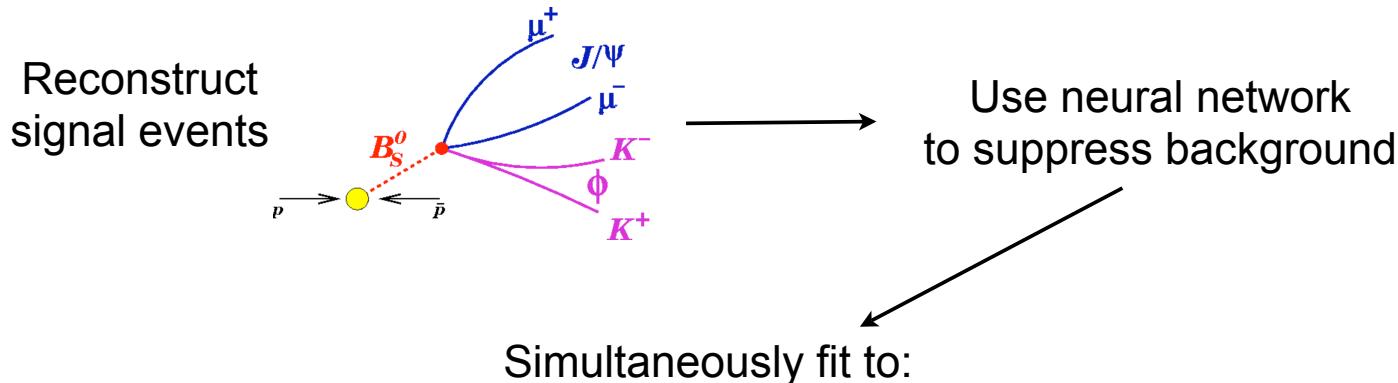
$$\boxed{\Delta \Gamma_s} = \Gamma_H - \Gamma_L \approx 2 |\Gamma_{12}| \cos(\phi_s) \quad \text{Lifetime/decay width difference}$$

$$\boxed{\phi_s} = \arg\left(\frac{-M_{12}}{\Gamma_{12}}\right) \quad \text{CP Phase}$$

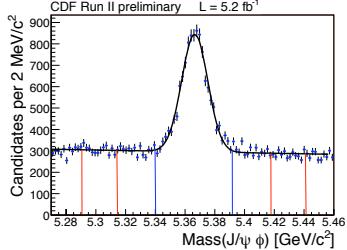
If a new phase,  $\phi_s^{NP}$  exists,  $\phi_s = \phi_s^{SM} + \phi_s^{NP} \sim \phi_s^{NP}$ ,  $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP} \sim -\phi_s^{NP}$

For large new physics phase,  $2\beta_s = -\phi_s^{NP} = -\phi_s$

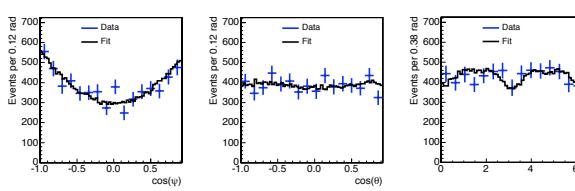
# Analysis Flow



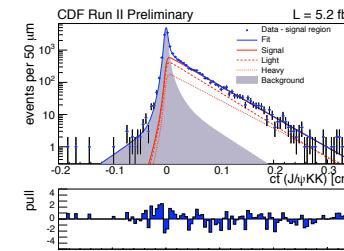
**Mass:**  
Separate signal from  
background



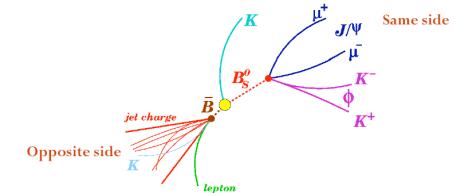
**Angular Distributions:**  
Separate CP-odd from  
CP-even contributions



**Lifetime:**  
Determine time  
dependence



**Apply flavor tagging:**  
Distinguish  $B^0_s$  from  
anti- $B^0_s$  at production



\*Must handle: angular efficiencies, flavor tagging calibration\*

# Likelihood Anatomy

- Probability density as a function of time and angles:

$$\left( \frac{d^4 P(t, \vec{\rho})}{dt d\vec{\rho}} \right)_{(B_s^0, \bar{B}_s^0)} \propto |A_0|^2 \mathcal{T}_{(+,+)} f_1(\vec{\rho}) + |A_{||}|^2 \mathcal{T}_{(+,+)} f_2(\vec{\rho}) + |A_{\perp}|^2 \mathcal{T}_{(-,-)} f_3(\vec{\rho}) \\ + |A_{||}| |A_{\perp}| \mathcal{U}_{(+,-)} f_4(\vec{\rho}) + |A_0| |A_{||}| \cos(\delta_{||}) \mathcal{T}_{(+,+)} f_5(\vec{\rho}) + |A_0| |A_{\perp}| \mathcal{V}_{(+,-)} f_6(\vec{\rho})$$

Time dependent terms:

$$\mathcal{T}_{\pm} = e^{-\Gamma t} [\cosh\left(\frac{\Delta\Gamma t}{2}\right) \mp \cos(2\beta_s) \sinh\left(\frac{\Delta\Gamma t}{2}\right) \mp \boxed{\eta \sin(2\beta_s) \sin(\Delta m_s t)}]$$

$$\mathcal{U}_{\pm} = \pm e^{-\Gamma t} [\sin(\delta_{\perp} - \delta_{||}) \cos(\Delta m_s t) - \boxed{\cos(\delta_{\perp} - \delta_{||}) \cos(2\beta_s) \sin(\Delta m_s t)} \pm \cos(\delta_{\perp} - \delta_{||}) \sin(2\beta_s) \sinh\left(\frac{\Delta\Gamma t}{2}\right)]$$

$$\mathcal{V}_{\pm} = \pm e^{-\Gamma t} [\sin(\delta_{\perp}) \cos(\Delta m_s t) - \boxed{\cos(\delta_{\perp}) \cos(2\beta_s) \sin(\Delta m_s t)} \pm \cos(\delta_{\perp}) \sin(2\beta_s) \sinh\left(\frac{\Delta\Gamma t}{2}\right)]$$

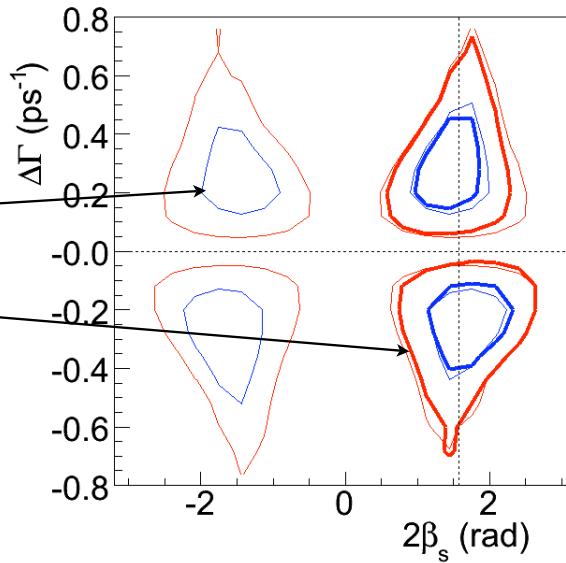
- Extract parameters of interest:  $\beta_s$ ,  $\Delta\Gamma$  (decay width difference),  $\tau(B_s^0)$  ( $B_s^0$  average lifetime),  $A_0$ ,  $A_{||}$ ,  $A_{\perp}$  (transversity amplitudes),  $\phi_{||}$ ,  $\phi_{\perp}$  (strong phases)

# Flavor Tagging and Likelihood Symmetries

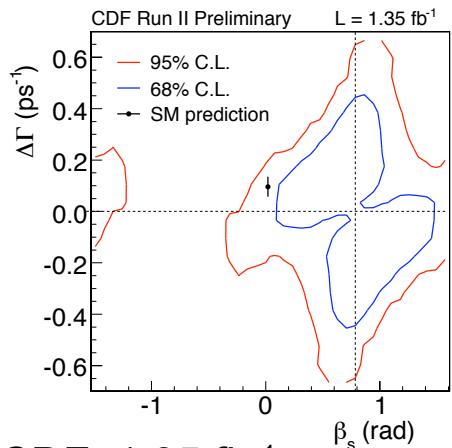
- Without flavor tagging, likelihood has two symmetries → four solutions
- $2\beta_s \rightarrow -2\beta_s, \delta_\perp \rightarrow \pi - \delta_\perp$
- $\Delta\Gamma \rightarrow -\Delta\Gamma, \delta_\parallel \rightarrow 2\pi - \delta_\parallel$
- Flavor tagging removes  $\beta_s \rightarrow -\beta_s$  symmetry → two solutions for  $\beta_s$  and  $\Delta\Gamma$

Toy Monte Carlo pseudo-experiment

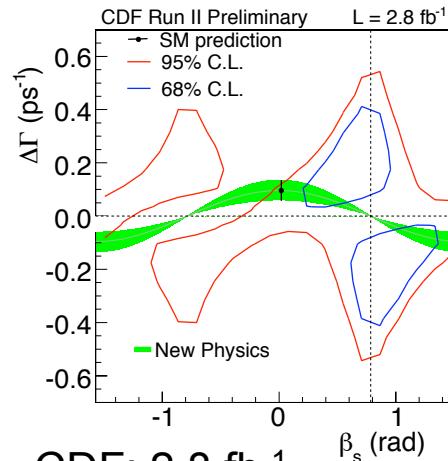
Untagged  
Tagged



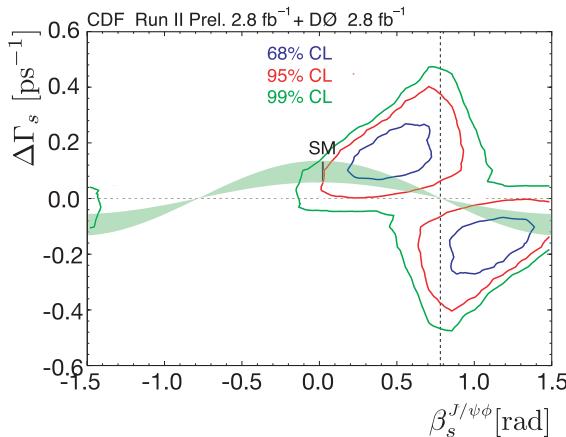
# Previous results



CDF:  $1.35 \text{ fb}^{-1}$   
1.5 $\sigma$  consistency with SM



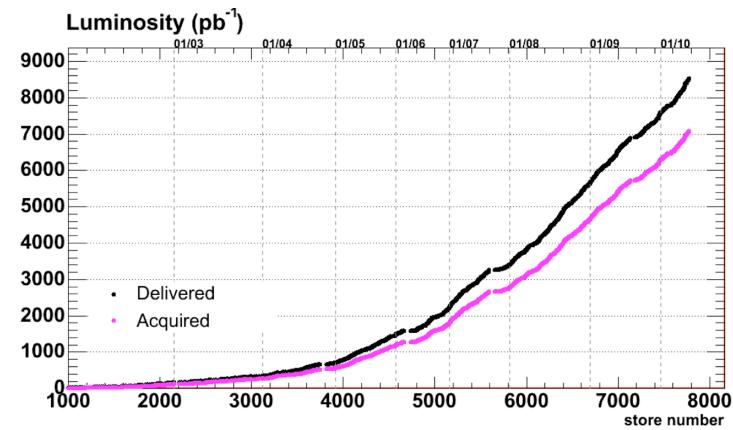
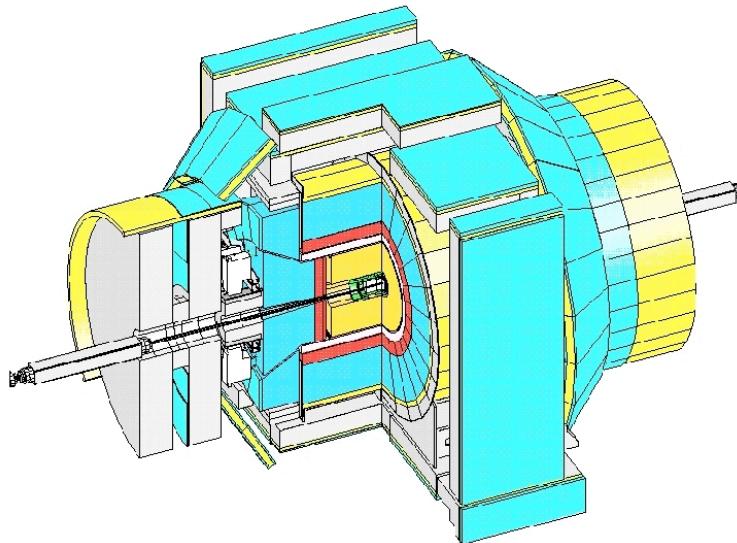
CDF:  $2.8 \text{ fb}^{-1}$   
1.8 $\sigma$  consistency with SM



CDF:  $2.8 \text{ fb}^{-1}$  + DØ:  $2.8 \text{ fb}^{-1}$   
2.3 $\sigma$  consistency with SM

# The Tevatron and CDF

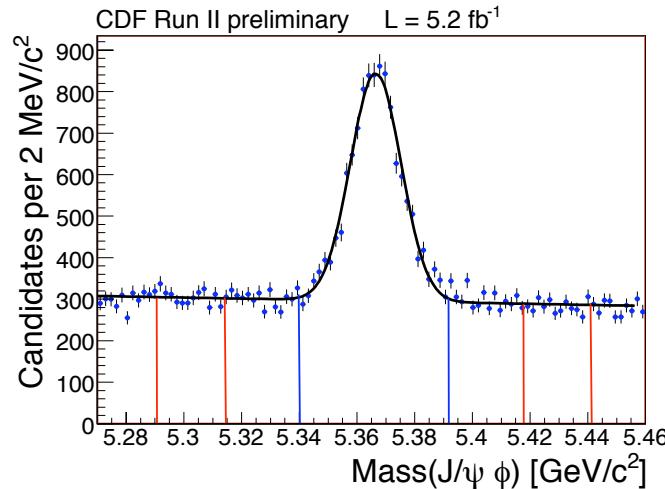
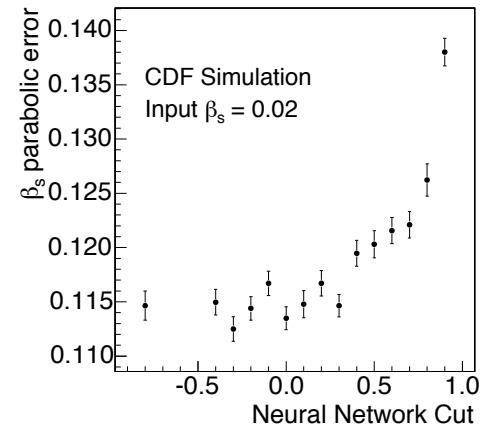
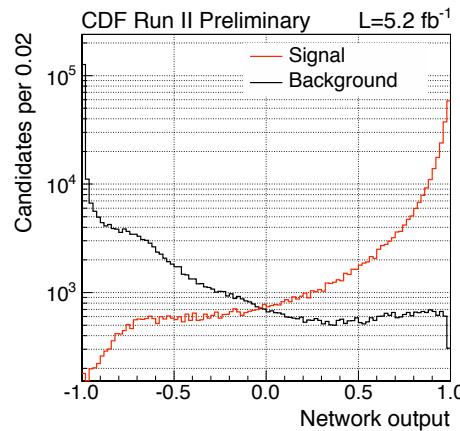
- p anti-p collisions at a center of mass energy of 1.96 TeV
- ~5  $\text{fb}^{-1}$  data used for this analysis



- Analysis relies on
  - Mass and decay time resolution (~0.1 ps compared to B lifetime ~1.5 ps)
  - Particle Identification

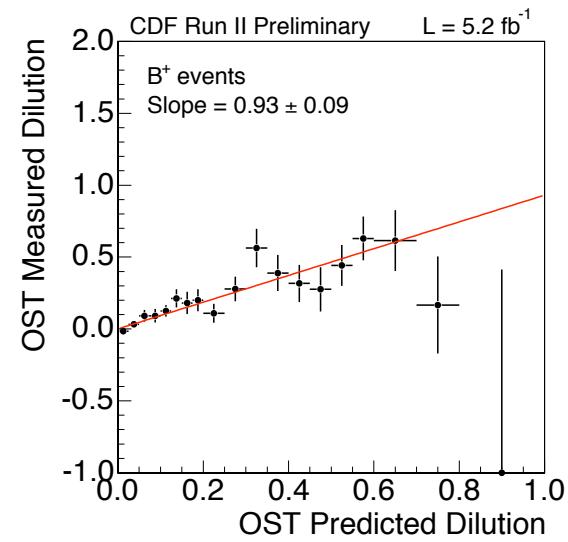
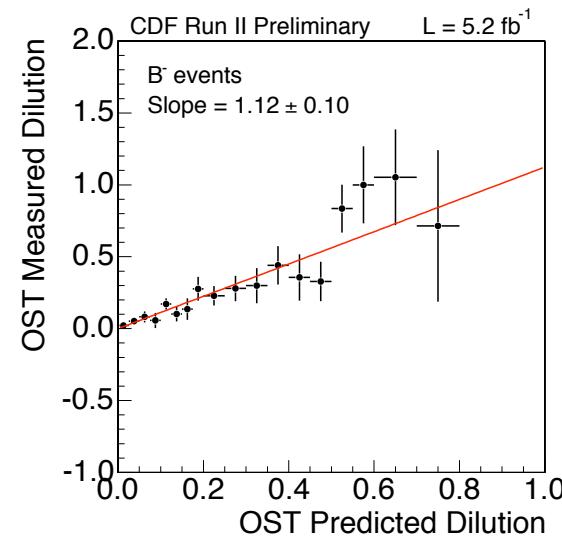
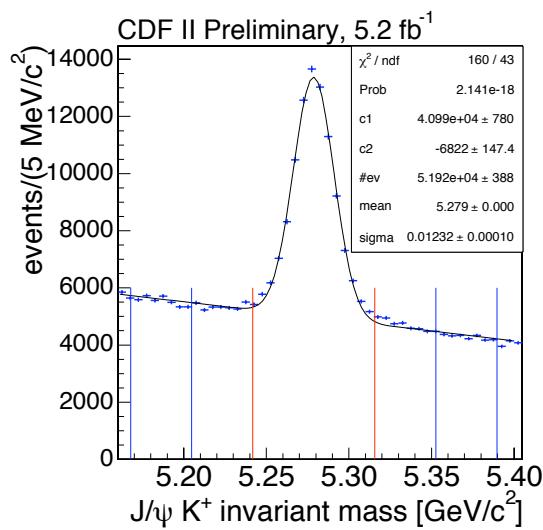
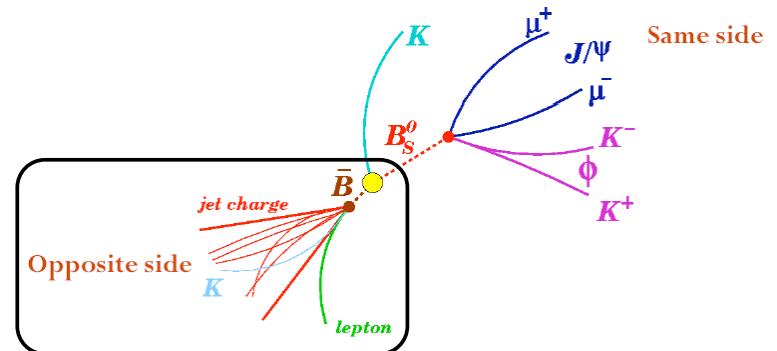
# Signal Selection

- Suppress background using artificial neural network
  - Training variables include  $p_T$  of tracks and decay particles, vertex probability for decay particles
  - Cut on neural network output is chosen by minimizing  $\beta_s$  errors on pseudo-experiments
  - Reconstruct  $\sim 6500$  signal events



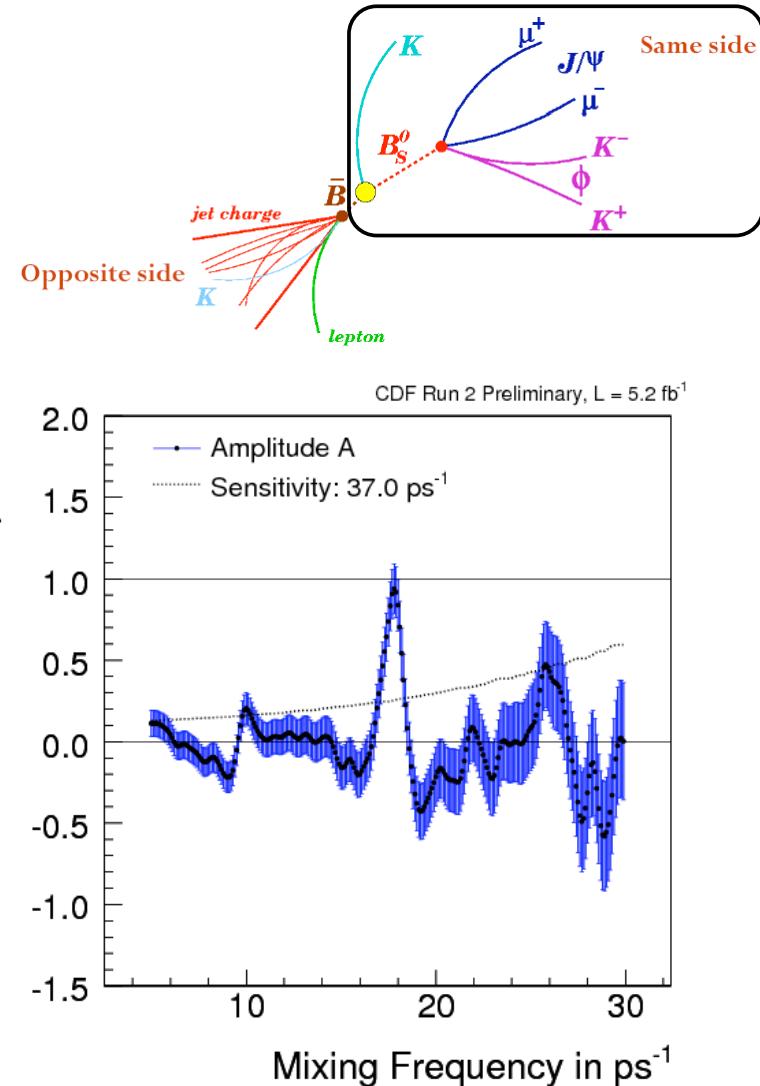
# OST Calibration

- Calibrate opposite side tagger on  $B^+ \rightarrow J/\Psi K^+$  events, which have same opposite side fragmentation behavior as  $B_s^0$
- $B^+ \rightarrow J/\Psi K^+$  decays are self-tagging
  - Compare measured to predicted dilution
  - Tagging power  $\epsilon D^2 = 1.2 \pm 0.2\%$



# SSKT Calibration

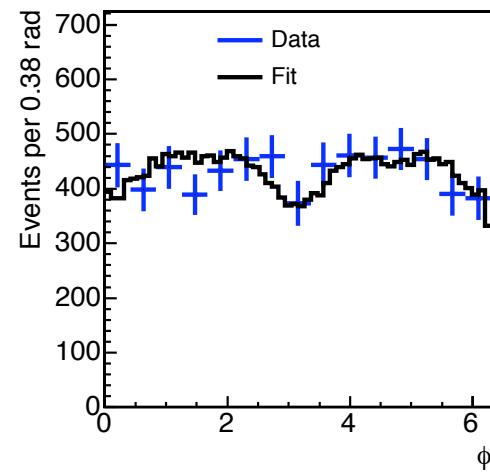
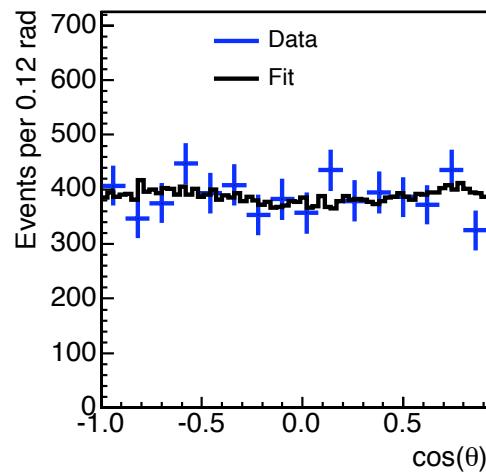
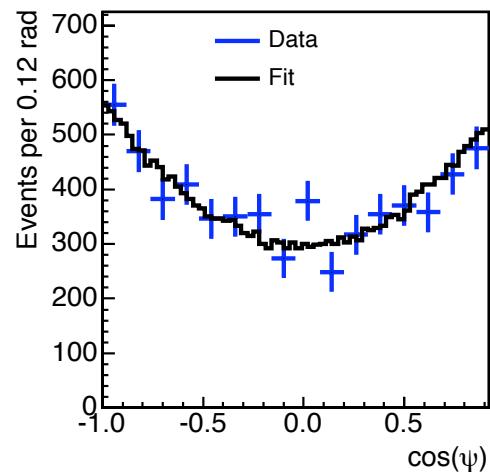
- Remeasured  $B_s^0$  mixing on  $5.2 \text{ fb}^{-1}$  of data
  - $B_s^0 \rightarrow D_s^- \pi^+$  and  $B_s^0 \rightarrow D_s^- (3\pi)^+$  channels
- For amplitude scan of  $\Delta m_s$ , probability normalized such that  $A=1$  at true value of  $\Delta m_s$ 
  - Measured amplitude relates measured to predicted dilution
  - $A = 0.94 \pm 0.15 \text{ (stat)} \pm 0.13 \text{ (syst)}$
  - $\Delta m_s = 17.79 \pm 0.07 \text{ ps}^{-1} \text{ (stat)}$   
(Consistent with world average)
  - Tagging power  $\varepsilon D^2 = 3.1 \pm 1.4\%$



# S-wave Contamination

- $B_s^0 \rightarrow J/\Psi K^+K^-$  and  $B_s^0 \rightarrow J/\Psi f_0$  could contaminate  $B_s^0 \rightarrow J/\Psi\phi$  signal and bias measurement of  $\beta_s$ 
  - Include possibility of non-resonant KK/f<sub>0</sub> in likelihood
  - Model KK and f<sub>0</sub> as flat in (narrow)  $\phi$  mass region
  - Model  $\phi$  as relativistic Breit-Wigner
  - Perform mass integration over  $\phi$  mass window
  - S-wave terms enter in angular part of likelihood

# Angular Analysis



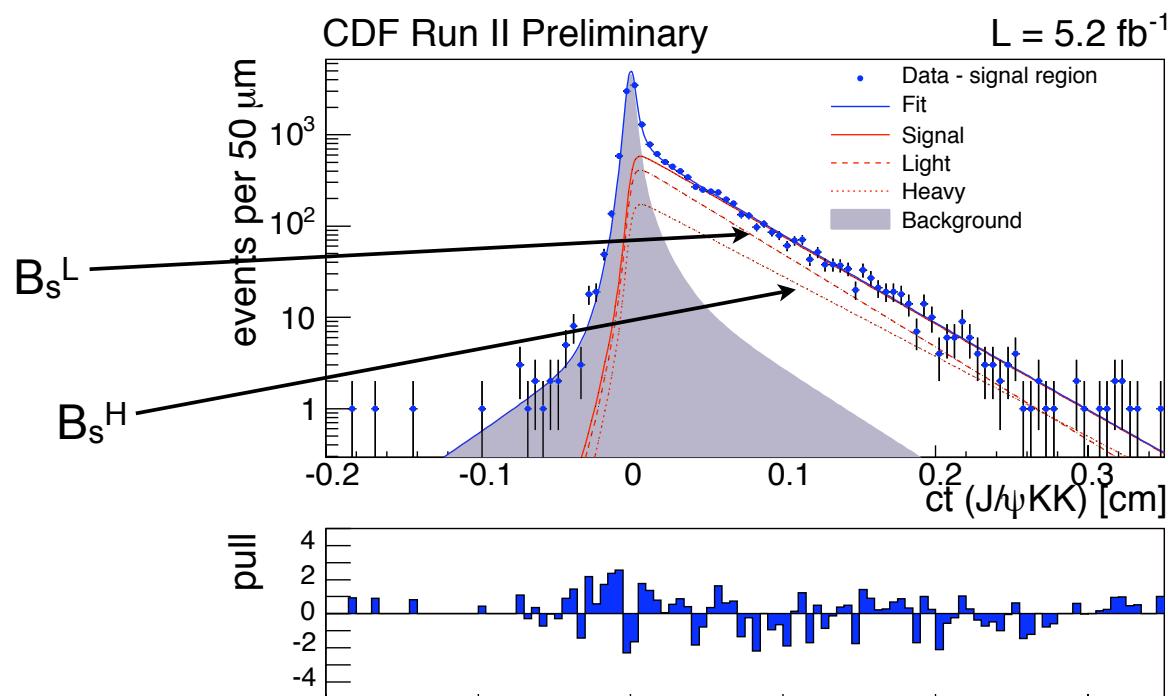
For Standard Model  $\beta_s$ :

$$|A_{||}(0)|^2 = 0.231 \pm 0.014(stat) \pm 0.015(syst)$$

$$|A_0(0)|^2 = 0.524 \pm 0.013(stat) \pm 0.015(syst)$$

$$\phi_{\perp} = 2.95 \pm 0.64(stat) \pm 0.07(syst)$$

# Lifetime Measurement



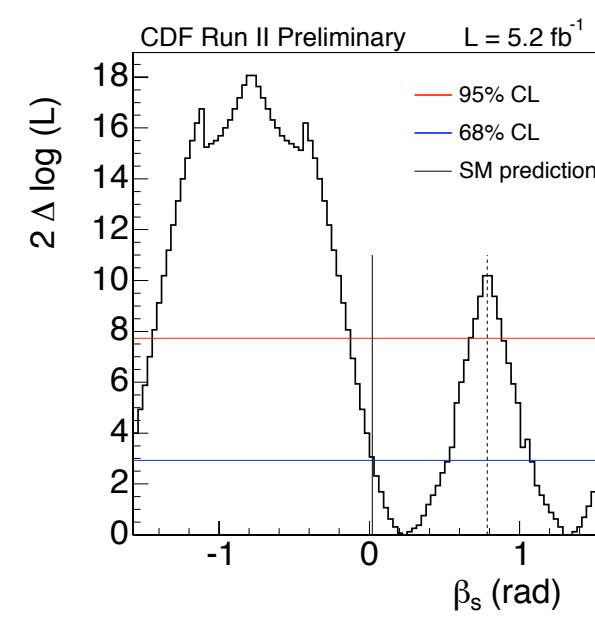
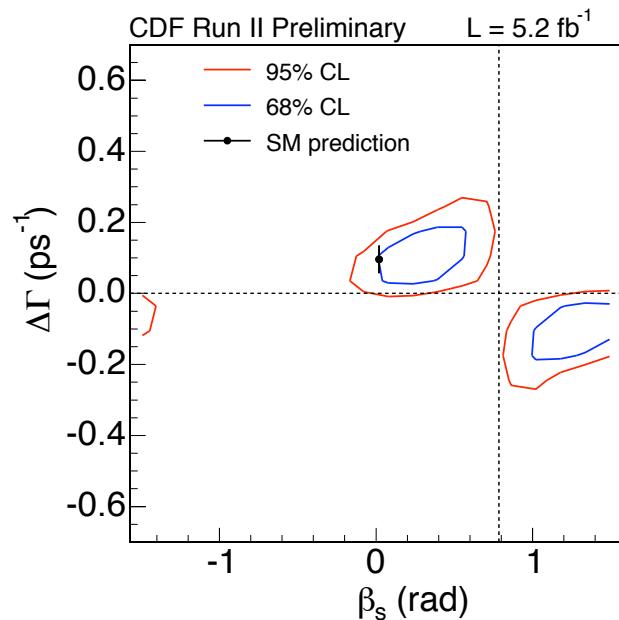
For Standard Model  $\beta_s$ :  
(World's best measurements)

$$c\tau_s = 458.7 \pm 7.5(\text{stat}) \pm 3.6(\text{syst}) \mu\text{m}$$

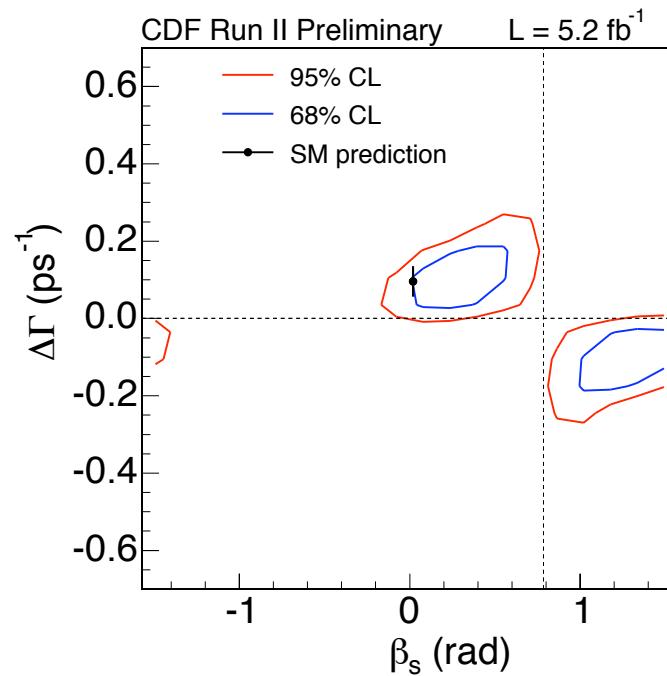
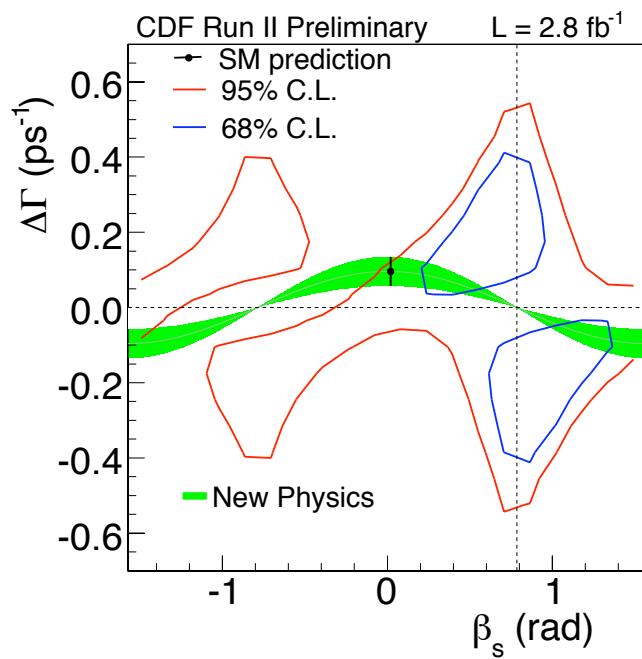
$$\Delta\Gamma_s = 0.075 \pm 0.035(\text{stat}) \pm 0.01(\text{syst}) \text{ ps}^{-1}$$

# $\beta_s$ - $\Delta\Gamma$ Contours

- Profile likelihood ordering technique used to guarantee coverage at 68% and 95% confidence levels
- 0.8 $\sigma$  consistency with SM
- $\beta_s \in [0.28, 0.52] \cup [1.08, 1.55]$  at 68% CL
- Similar consistency with SM to 2D case



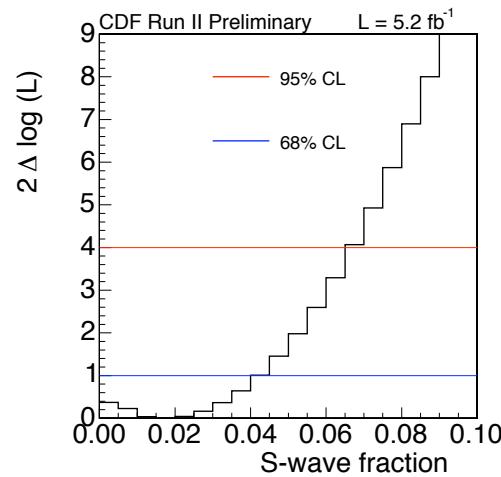
# Comparison to Previous Measurement



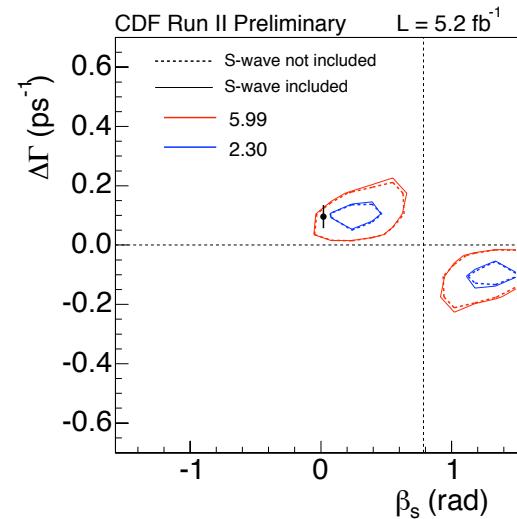
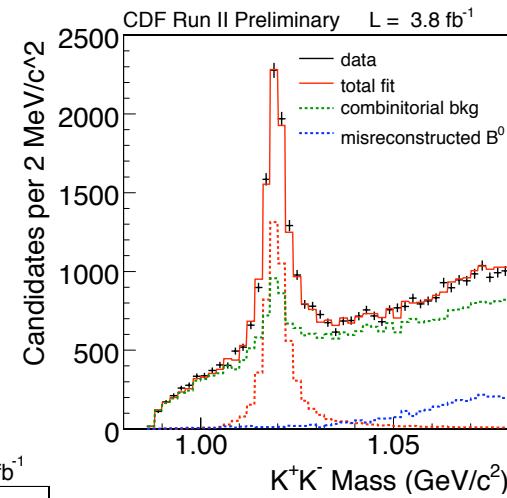
Size of contour has decreased significantly with increased statistics and analysis improvements

# Effect of S-wave

Likelihood scan of S-wave fraction finds  
S-wave contamination <7% at 95% CL



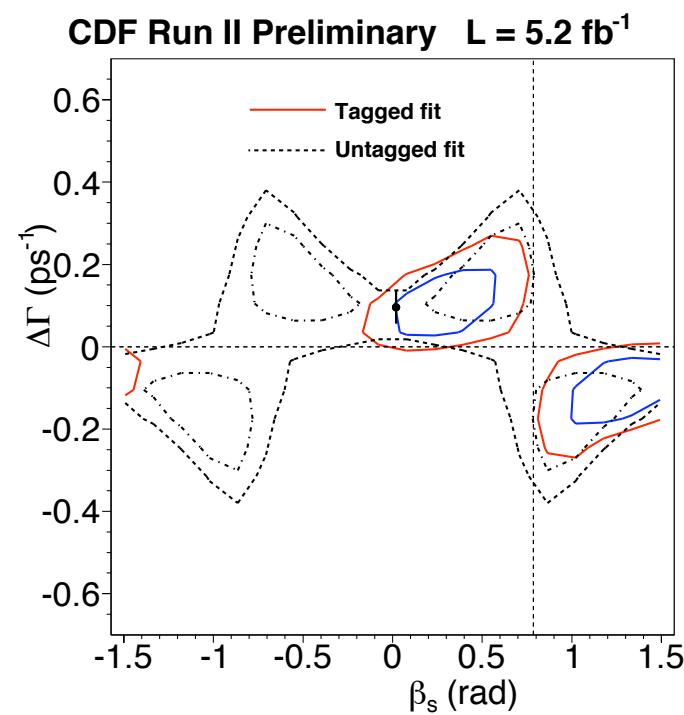
A fit to KK invariant mass does not  
show large S-wave contamination



$\beta_s$ - $\Delta\Gamma$  contour with S-wave  
included in fit is not  
significantly different  
than fit without S-wave

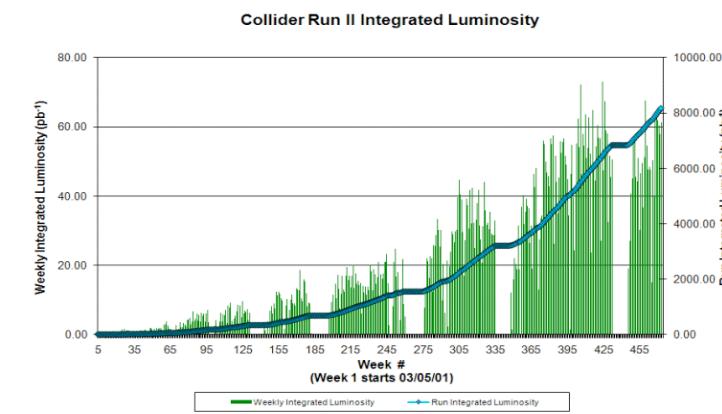
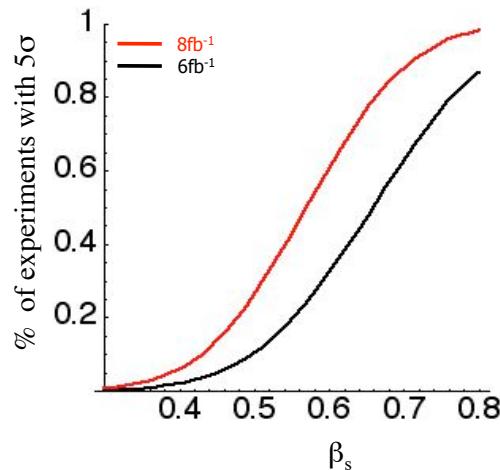
# Tagged versus Untagged Contours

Good agreement  
between contours  
with and without  
flavor tagging  
included in fit



# Conclusions

- Latest measurement of  $\beta_s$  using  $B_s^0 \rightarrow J/\Psi \phi$  decays
- Errors on  $\beta_s$  have decreased significantly from previous measurements
- Consistency with Standard Model expectation has improved from previous measurements
- CDF will double data sample by end of Run II, allowing even more precise measurement
- More details: CDF public note 10206, PRL 100, 161802 (2008)



# Backup

# Detector Sculpting

- Account for detector sculpting of transversity angles
  - Calculate angular efficiencies on realistic  $B_s^0 \rightarrow J/\Psi \phi$  Monte Carlo
  - Generate angles flat
  - Parameterize after going through full CDF reconstruction

